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CP violation in Hyperon decays

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Abstract

The CP properties in hyperon decays are briefly reviewed. We discuss the general phenomenology and define CP odd observables in hyperon decays. With these observables, we discuss the predictions of some models and their observational potential.

1 Introduction

More than thirty years after its discovery[1], the origin of CP violation still puzzles most of theoretical and experimental physicists. It remains one of the most important questions in physics. Until today, the effects of CP violation has been measured only in kaon system. In kaon deacys, two parameters, ϵ and ϵ', are needed to describe CP violation which represent the indirect and direct CP violating mechanism. The current experimental value for ϵ is[2]

$$|\epsilon| = 2.26 \times 10^{-3}, \tag{1}$$

In suitable convention, ϵ can be associated with the imaginary part of $K - \bar{K}$ mixing; and it denotes $|\Delta S| = 2$ process. However, the experimental situation for direct CP violating parameter ϵ' is still ambiguous. Its measured values are [3, 4]

$$\frac{\epsilon'}{\epsilon} = \begin{cases} (2.3 \pm 0.65) \times 10^{-3} & \text{NA31,} \\ (0.74 \pm 0.52 \pm 0.29) \times 10^{-3} & \text{E731.} \end{cases} \tag{2}$$

If ϵ' turns out to be nonzero, it would indicate the existence of direct $|\Delta S| = 1$ CP violation. Nonleptonic hyperon decays of Λ, Σ and Ξ provide a direct probe into the potential $\Delta S = 1$ CP nonconservation. It is a particularly interesting system because it contains more than one angular momentum channels and more than one isospin channels also. Therefore the system provides a variety of ways for amplitudes to interefere which is essential for CP violation to be observable. It is also interesting because E871 experiment at Fermilab [7] will measure CP violation in $\Xi^- \to \Lambda\pi^-$ and $\Lambda \to p\pi^-$ using 2^9 Ξ^- and $\bar{\Xi}^+$ produced by colliding 800 GeV proton with fixed target. $\Xi \to \Lambda$ is particularly interesting because one needs spin information to measure CP violation in hyperon decays. The spin information for Λ can be obtained from the angular distribution of its two body decay. Experience from E756 indicates they can collect 2×10^7 events per day with very simple trigger. With 200 days running time, the expected sensitivity for CP violating asymmetry is about 10^{-4} for $A(\Lambda^0_-) + A(\Xi^-_-)$ in the first run which is not too far from the prediction of SM of a few $\times 10^{-5}$ with large uncertainty. If The sensitivity may be improved in the future runs. The main limiting factor seems to be whether the chamber can tolerate the large flux corresponding to collecting 1400 $\bar{\Xi}^+$ decays per second. Theoretically the most serious obstacle against having large CP odd observable, A, comes from the serious constraint from the current limit on ϵ'. However, the two parameters in principle measure different $\Delta S = 1$ interactions. One of the theoretical challenges is to disintangle the two obersvables within various models.

This article is organized as follows. In section 2 we make the phenomenological analysis, define the CP odd observables and formulate the relationships between the phe-

nomenological parameters and the CP odd observables. In section 3 we compare the predictions of various models, including SM. Finally we give some concluding remarks.

2 Phenomenological Analysis

2.1 CP odd observables

For $J^P = \frac{1}{2}^+$ hyperon, the most general decay amplitude is [8, 9, 10]

$$\mathcal{M} = G_F m_\pi^2 \bar{u_f}(a - b\gamma_5)u_i, \tag{3}$$

where a and b are constants. G_F is the Fermi constant, m_π is the mass of π meson and $u_{i,f}$ denote the initial and final baryon states. Due to the negative intrinsic parity of π meson, the a and b terms denote parity violating and conserving process respectively. The matrix element can be reduced to

$$\mathcal{M}(B_i \to B_f \pi) = S + P\vec{\sigma} \cdot \hat{q}, \tag{4}$$

where $\hat{q}$ is the direction of final baryon B_f momentum. $S = a$ is the amplitude with the final state in the S-wave, $\ell = 0$, parity-odd state; and $P = |\vec{q}|b/(E_f + M_f)$ denotes the amplitude with the final state in the P-wave, $\ell = 1$, parity-even state. In terms of these quantities the transition rate can be denoted by

$$\frac{4\pi}{\Gamma}\frac{d\Gamma}{d\Omega} = 1 + \alpha\hat{s}_i \cdot \hat{q} + \hat{s}_f \cdot [(\alpha + \hat{s}_i \cdot \hat{q})\hat{q} + \beta\hat{s}_i \times \hat{q} + \gamma(\hat{q} \times (\hat{s}_i \times \hat{q}))], \tag{5}$$

in the rest frame of the initial hyperon, where $\hat{s}_{i,f}$ are the spin vectors of the initial and final baryons, respectively. Γ is the total decay rate given by

$$\Gamma = \frac{|\vec{q}|(E_f + E_i)}{4\pi m_i} G_F^2 m_\pi^4 (|S|^2 + |P|^2). \tag{6}$$

The parameters of α, β and γ is defined as

$$\alpha = 2\frac{Re(S^*P)}{|S|^2 + |P|^2}, \quad \beta = 2\frac{Im(S^*P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}. \tag{7}$$

The three parameters, α, β and γ, are not independent, since

$$\alpha^2 + \beta^2 + \gamma^2 = 1. \tag{8}$$

Therefore β, γ can be parametrized by an angle ϕ as $\beta = (1 - \alpha^2)^{1/2} sin\phi$, $\gamma = (1 - \alpha^2)^{1/2} cos\phi$. Note that α involves only one spin and it is $\hat{T}$ even (we shall define $\hat{T}$ as the transformation that reverse all the directions of all the vectors but keep the initial state and final state intact); β involves only two spins and is $\hat{T}$ odd and γ involves only two

spins and is $\hat{T}$ even. Therefore, β and γ, which involves two and three vectors respectively, are intrinsincally harder to measure than α. Since $\hat{T}$ is not time reversal, even without CP violation, the final state interaction (FSI) can produce $\hat{T}$-odd effect also. Therefore, a nonvanishing β can be due to either FSI or CP violation.

If one does not measure $\hat{s}_f$, the decay distribution of B_f is

$$\frac{4\pi}{\Gamma}\frac{d\Gamma}{d\Omega} = 1 + \alpha \vec{P}_i \cdot \hat{q}, \tag{9}$$

where $\vec{P}_i$ is the polarization of B_i. Therefore, the decay distribution of B_f can be used to measure the polarization of B_i. In general, the polarization of B_f is given by

$$\vec{P}_f = \frac{(\alpha + \vec{P}_i \cdot \hat{q})\hat{q} + \beta \vec{P}_i \times \hat{q} + \gamma(\hat{q} \times (\vec{P}_i \times \hat{q}))}{1 + \alpha \vec{P}_i \cdot \hat{q}}. \tag{10}$$

Therefore, $\vec{P}_f = \alpha\hat{q}$ if $\vec{P}_i = 0$. In $\Xi^- \to \Lambda + \pi \to p\pi\pi$, if Ξ^- is produced unpolarized as in E871 experimental design, then $\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda$, and the decay distribution proton is

$$\frac{4\pi}{\Gamma_p}\frac{d\Gamma_p}{d\Omega} = 1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{q} = 1 + \mathbf{a}\hat{p}_\Lambda \cdot \hat{q}, \tag{11}$$

where $\mathbf{a}$ is $\alpha_\Lambda \alpha_\Xi$. Similarly one can define $\bar{\mathbf{a}}$ in $\bar{\Xi}$ decay. E871 experiment will measure $\delta\mathbf{a} = (\mathbf{a} - \bar{\mathbf{a}})/(\mathbf{a} + \bar{\mathbf{a}})$ which is rouhgly $A(\Lambda) + A(\Xi)$. Note however, there may be a small polarization of Ξ due to the interference between strong and weak process in the production. In that case, one can still measure Ξ polarization directly by determining the Λ momentum precisely.

The amplitudes of S and P in Eq.(4), in general, are complex numbers. They can be parametrized as[11, 12]:

$$\begin{aligned} S &= \sum_i S_i e^{i(\delta_i^S + \theta_i^S)}, \\ P &= \sum_i P_i e^{i(\delta_i^P + \theta_i^P)}. \end{aligned} \tag{12}$$

Here we have extracted the strong rescattering phases δ_i and the weak CP violating phases θ_i from the amplitudes and S_i and P_i are real where i represents all possible final isospin states with changes in isospin ΔI. The parameters for antihyperon decays can be defined similarly, but denoted by $\bar{\Gamma}$, $\bar{\alpha}$, $\bar{\beta}$ and $\bar{\gamma}$. In our convention, the antihyperon decay amplitudes are

$$\begin{aligned} \bar{S} &= -\sum_i S_i e^{i(\delta_i^S - \theta_i^S)}, \\ \bar{P} &= \sum_i P_i e^{i(\delta_i^P - \theta_i^P)}. \end{aligned} \tag{13}$$

The minus(−) sign in the S-wave amplitude comes from the fact that pion is parity-odd, that is, under parity transformation parity violating S amplitude will appear with an extra $-$ sign in the amplitude. On the other hand, according to CPT theorem, the amplitude of hyperon in weak interaction will relate to the amplitude of antihyperon by complex conjugation. So, the amplitudes of antihyperon are shown as Eq.(13). Using Eq.(12) and Eq.(13) we can show

$$\alpha \xleftrightarrow{CP} -\bar{\alpha}, \qquad \beta \xleftrightarrow{CP} -\bar{\beta}. \tag{14}$$

Using these parameters, we can define some CP asymmetric quantities in hyperon decays [12]:

$$\begin{aligned} \Delta &\equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, \\ A &\equiv \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}}, \\ B &\equiv \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}}, \\ B' &\equiv \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}}. \end{aligned} \tag{15}$$

According to the results of Eq.(14) and Eq.(15), when CP is conserved we have $\Gamma = \bar{\Gamma}$ $\alpha = -\bar{\alpha}$ and $\beta = -\bar{\beta}$; and CP asymmetric quantities, defined in Eq.(15), all vanish. When CP$\hat{T}$ is conserved, we have $\Gamma = \bar{\Gamma}$ $\alpha = -\bar{\alpha}$ and $\beta = +\bar{\beta}$. Therefore, to have nonzero Δ, one needs FSI and interference between different isospin channels (instead of momentum channels). Therefore Δ is necessarily suppressed by $\Delta I = 1/2$ rule. On the other hand, again due to the $\Delta I = 1/2$ rule, the leading contributions to A, B and B' should be due to the interference between different momentum channels(S and P waves channels). Nonvanishing A also requires FSI. On the other hand B actually gets a spurious enhancement due to the FSI suppression in the denominator. In the following section we will discuss the simplified relation between CP violating phases and physical measurements.

2.2 Isospin Decomposition

The Hamiltonian of $\Delta S = 1$ in hyperon decays includes two different isospin terms that one is $\Delta I = 1/2$ and $\Delta I = 3/2$ is another one. Therefore, using the parametrization of Eq.(12) we can write them to be [13]

$$\Lambda \longrightarrow p\pi^- : \qquad S(\Lambda^0_-) = -\sqrt{\frac{2}{3}}S_{11}e^{i(\delta_1+\theta_1^S)} + \sqrt{\frac{1}{3}}S_{33}e^{i(\delta_3+\theta_3^S)},$$

$$
\begin{aligned}
& & P(\Lambda^0_-) &= -\sqrt{\frac{2}{3}}P_{11}e^{i(\delta_{11}+\theta^P_1)} + \sqrt{\frac{1}{3}}P_{33}e^{i(\delta_{31}+\theta^P_3)}, \\
&\Lambda \longrightarrow n\pi^0: & S(\Lambda^0_0) &= \sqrt{\frac{1}{3}}S_{11}e^{i(\delta_1+\theta^S_1)} + \sqrt{\frac{2}{3}}S_{33}e^{i(\delta_3+\theta^S_3)}, \\
& & P(\Lambda^0_0) &= \sqrt{\frac{1}{3}}P_{11}e^{i(\delta_{11}+\theta^P_1)} + \sqrt{\frac{2}{3}}P_{33}e^{i(\delta_{31}+\theta^P_3)}, \\
&\Xi^- \longrightarrow \Lambda\pi^-: & S(\Xi^-_-) &= S_{12}e^{i(\delta_2+\theta^S_{12})} + \frac{1}{2}S_{32}e^{i(\delta_2+\theta^S_{32})}, \\
& & P(\Xi^-_-) &= P_{12}e^{i(\delta_{21}+\theta^P_{12})} + \frac{1}{2}P_{32}e^{i(\delta_{21}+\theta^P_{32})}, \\
&\Xi^0 \longrightarrow \Lambda\pi^0: & S(\Xi^0_0) &= \sqrt{\frac{1}{2}}(S_{12}e^{i(\delta_2+\theta^S_{12})} - S_{32}e^{i(\delta_2+\theta^S_{32})}), \\
& & P(\Xi^0_0) &= \sqrt{\frac{1}{2}}(P_{12}e^{i(\delta_{21}+\theta^P_{12})} - P_{32}e^{i(\delta_{21}+\theta^P_{32})}). \qquad (16)
\end{aligned}
$$

Where S_{ij}, P_{ij} correspond to $S_{2\Delta I,2I}, P_{2\Delta I,2I}$, and δ_{2I} and $\delta_{2I,1}$ for S-wave and P-wave amplitudes , respectively. It is well known experimentally that the $\Delta I = 1/2$ amplitude is dominant. If we take first order in the $\Delta I = 3/2$ amplitudes, we can simplify Eq.(13) as follows [12]:

$$
\begin{aligned}
\Delta(\Lambda^0_-) &= \sqrt{2}\frac{S_{33}}{S_{11}} sin(\delta_3-\delta_1)sin(\theta^S_3-\theta^S_1), \qquad (17.a)\\
A(\Lambda^0_-) &= -tan(\delta_{11}-\delta_1)sin(\theta^P_1-\theta^S_1)\times \\
&\left[1+\frac{1}{\sqrt{2}}\frac{S_{33}}{S_{11}}\left[\frac{cos(\delta_{11}-\delta_3)}{cos(\delta_{11}-\delta_1)} - \frac{sin(\delta_{11}-\delta_3)}{sin(\delta_{11}-\delta_1)}\frac{sin(\theta^P_1-\theta^S_3)}{sin(\theta^P_1-\theta^S_1)}\right]\right.\\
&\left.+\frac{1}{\sqrt{2}}\frac{P_{33}}{P_{11}}\left[\frac{cos(\delta_{31}-\delta_1)}{cos(\delta_{11}-\delta_1)} - \frac{sin(\delta_{31}-\delta_1)}{sin(\delta_{11}-\delta_1)}\frac{sin(\theta^P_3-\theta^S_1)}{sin(\theta^P_1-\theta^S_1)}\right]\right], \qquad (17.b)\\
B(\Lambda^0_-) &= cot(\delta_{11}-\delta_1)sin(\theta^P_1-\theta^S_1)\times \\
&\left[1+\frac{1}{\sqrt{2}}\frac{S_{33}}{S_{11}}\left[\frac{sin(\delta_{11}-\delta_3)}{sin(\delta_{11}-\delta_1)} - \frac{cos(\delta_{11}-\delta_3)}{cos(\delta_{11}-\delta_1)}\frac{sin(\theta^P_1-\theta^S_3)}{sin(\theta^P_1-\theta^S_1)}\right]\right.\\
&\left.+\frac{1}{\sqrt{2}}\frac{P_{33}}{P_{11}}\left[\frac{sin(\delta_{31}-\delta_1)}{sin(\delta_{11}-\delta_1)} - \frac{cos(\delta_{31}-\delta_1)}{cos(\delta_{11}-\delta_1)}\frac{sin(\theta^P_3-\theta^S_1)}{sin(\theta^P_1-\theta^S_1)}\right]\right]. \qquad (17.c)
\end{aligned}
$$

To first order in the $\Delta I = 3/2$ amplitudes we have

$$
\begin{aligned}
\Delta(\Lambda^0_0) &= -\frac{1}{2}\Delta(\Lambda^0_-), \\
A(\Lambda^0_0) &= A(\Lambda^0_-), \\
B(\Lambda^0_0) &= B(\Lambda^0_-). \qquad (18)
\end{aligned}
$$

From Nπ scattering, the strong rescattering phases for Λ decay can be determined to be [14]

$$
\begin{aligned}
&\delta_1 \approx 6.0^o,\ \delta_3 \approx -3.8^o, \\
&\delta_{11} \approx -1.1^o,\ \delta_{31} \approx -0.7^o \qquad (19)
\end{aligned}
$$

with errors of order 1^o. The amplitudes giving Experimental measurements that reflect $\Delta I = 1/2$ rule give $S_{33}/S_{11} = 0.027 \pm 0.008$ and $P_{33}/P_{11} = 0.03 \pm 0.037$ [15].

The decay amplitudes for $\Xi^- \to \Lambda^0\pi^-$ are

$$\begin{aligned}
\Delta(\Xi^-_-) &= 0, && (20.a)\\
A(\Xi^-_-) &= -tan(\delta_{21}-\delta_2)\Big[sin(\theta^P_{12}-\theta^S_{12}) \\
&\quad +\frac{1}{2}\frac{P_{32}}{P_{12}}(sin(\theta^S_{32}-\theta^P_{12})-1)+\frac{1}{2}\frac{S_{32}}{S_{12}}(sin(\theta^P_{12}-\theta^S_{32})-1)\Big], && (20.b)\\
B(\Xi^-_-) &= cot(\delta_{21}-\delta_2)\Big[sin(\theta^P_{12}-\theta^S_{12}) \\
&\quad +\frac{1}{2}\frac{P_{32}}{P_{12}}(sin(\theta^S_{32}-\theta^P_{12})-1)+\frac{1}{2}\frac{S_{32}}{S_{12}}(sin(\theta^P_{12}-\theta^S_{32})-1)\Big]. && (20.c)
\end{aligned}$$

If $\Delta I = 3/2$ contributions are treated to lowest order, we have

$$\begin{aligned}
\Delta(\Xi^0_0) &= 0,\\
A(\Xi^0_0) &= A(\Xi^-_-),\\
B(\Xi^0_0) &= B(\Xi^-_-). && (21)
\end{aligned}$$

The strong rescattering phases for Ξ decays hasnot been measured experimentally. Recently, Lu, Savage and Wise, using chiral perturbation theory, predict $\delta_{21} = -1.7^0$ and $\delta_2 = 0$ [16]. The ratio of $\Delta I = 3/2$ amplitudes to that of $\Delta I = 1/2$ in Ξ decays are similar to those in Λ decays and the experimental measurements are: $S_{32}/S_{12} = -0.046 \pm 0.014$ and $P_{32}/P_{12} = -0.01 \pm 0.04$ [15]. The equality $\Delta(\Xi^0_0) = \Delta(\Xi^-_-) = 0$ is exact. This is because there is only one final state isospin I=1 in Ξ decays. As a result, no final state phase difference is possible.

In order to obtain the predictions in various models more easily, in the literature one continue to simplify the formula of CP violating observables shown in Eqs.(15) and Eqs.(18). These formula can be written as following [17, 18]:

$$\begin{aligned}
\Delta(\Lambda^0_-) &= -2\Delta(\Lambda^0_0) = \sqrt{2}\frac{S_{33}}{S_{11}}sin(\delta_3-\delta_1)sin(\theta^S_3-\theta^S_1),\\
A(\Lambda^0_-) &= A(\Lambda^0_0) = -tan(\delta_{11}-\delta_1)sin(\theta^P_1-\theta^S_1),\\
B(\Lambda^0_-) &= B(\Lambda^0_0) = cot(\delta_{11}-\delta_1)sin(\theta^P_1-\theta^S_1),\\
\Delta(\Xi^-_-) &= \Delta(\Xi^0_0) = 0,\\
A(\Xi^-_-) &= A(\Xi^0_0) = -tan(\delta_{21}-\delta_2)sin(\theta^P_{12}-\theta^S_{12}),\\
B(\Xi^-_-) &= B(\Xi^0_0) = cot(\delta_{21}-\delta_2)sin(\theta^P_{12}-\theta^S_{12}). && (22)
\end{aligned}$$

We have neglected the contributions of $\Delta I = 3/2$ in the CP violating observables except in Δ.

The remaining task is to calculate weak interaction phases θ_i's which in turn depend on the model for CP violation. In following section we discuss the predictions of various models.

3 Theoretical Predictions

We summary the consequences of various CP violating models that has been discussed in the literature [17, 18]in terms of tabular form, and their predictions are as following:

Table 1. Some models of CP violation in Hyperon decay.

Λ decay	KM model	Weinberg Model	Left-Right Model
$\Delta(\Lambda^0_-)$	$< 10^{-6}$	-0.8×10^{-5}	0
$A(\Lambda^0_-)$	$-(1 \sim 5) \times 10^{-5}$	-2.5×10^{-5}	-6×10^{-4}
$B(\Lambda^0_-)$	$(0.6 \sim 3) \times 10^{-3}$	1.6×10^{-3}	3.87×10^{-2}
Ξ decay			
$\Delta(\Xi^-_-)$	0	0	0
$A(\Xi^-_-)$	$(1 \sim 10) \times 10^{-6}$	3.31×10^{-5}	2.59×10^{-6}
$B(\Xi^-_-)$	$-(1 \sim 10) \times 10^{-3}$	-3.76×10^{-2}	-2.94×10^{-3}

In Left-Right Model for Λ decay, we have used the numerical results of Ref.[19]. For Ξ decays, the calculated results of Ref.[16] with chiral perturbation have been used. From Table 1. we see that Δ is very small. Experimentally, it may be difficult to measure it. However, the prediction for the CP violating observable A is close to the region which will be probed by the E871 experiment with experimental sensitivity 10^{-4} to 10^{-5} in A_{asy}.

4 Summary

The minimal SM of electroweak interaction is in very good agreement with all experimental data so far, and there is no evidence for any new particles or interactions below electroweak scale. Although SM can give us CP violating effects through three generation naturally, CP violation is still not considered satisfactorily understood.

Here we have studied the phenomenology and introduced some models to predict the CP odd observables $\Delta(\Lambda), A(\Lambda)$ and $B(\Lambda)$ in hyperon system. If we want to measure these direct CP asymmetry, final state interactions are important. From our analysis, we know that the predictions in SM are near the experimental sensitivity in E871; and the predictions in WTHDM seem hard to reach in the future. However, as we have shown in left-right model, it may be the first candidate which can be measured or tested in E871 proposal.

Given the crude estimates of the hadronic matrix elements involved in various models, all the numerical results should be viewed with caution. Nevertheless, the results , in

especial left-right model, suggest that the search for CP violation in $A(\Lambda)$ at the 10^{-4} level of sensitivity that is expected for E871 is potentially very interesting and could reach. The suggestion is not only that we can understand the mechanism of CP violation but also that we may have the chance to find out new physics and further understand the physics at electroweak scale. Besides SM, WTHDM and left-right symmetric model, theoretically, we may also consider the contribution of the other models such as supersymmetric model or unified theory. Whatever we bulid the models, we still hope that the experiment could tell us what CP violation is. We need more experimental data to get the nontrivial values for neutron electric dipole moment (NEDM) and ϵ'/ϵ.

We conclude that it is possible for E871 to observe a CP violating signal at the 10^{-4} level.

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